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Letter to the Editor

# The INTEGRAL mission

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**Abstract.** The ESA observatory INTEGRAL (International Gamma-Ray Astrophysics Laboratory) is dedicated to the fine spectroscopy (2.5 keV FWHM @ 1 MeV) and fine imaging (angular resolution: 12 arcmin FWHM) of celestial gamma-ray sources in the energy range 15 keV to 10 MeV with concurrent source monitoring in the X-ray (3−35 keV) and optical (*V*-band, 550 nm) energy ranges. INTEGRAL carries two main gamma-ray instruments, the spectrometer SPI (Vedrenne et al. 2003) – optimized for the high-resolution gamma-ray line spectroscopy (20 keV–8 MeV), and the imager IBIS (Ubertini et al. 2003) – optimized for high-angular resolution imaging (15 keV–10 MeV). Two monitors, JEM-X (Lund et al. 2003) in the (3−35) keV X-ray band, and OMC (Mas-Hesse et al. 2003) in optical Johnson *V*-band complement the payload. The ground segment includes the Mission Operations Centre at ESOC, ESA and NASA ground stations, the Science Operations Centre at ESTEC and the Science Data Centre near Geneva. INTEGRAL was launched on 17 October 2002. The observing programme is well underway and sky exposure (until June 2003) reaches ~1800 ks in the Galactic plane. The prospects are excellent for the scientific community to observe the high energy sky using state-of-the-art gamma-ray imaging and spectroscopy. This paper presents a high-level overview of INTEGRAL.

**Key words.** gamma-ray astronomy – space observatory

## 1. Introduction

The ESA observatory INTEGRAL (International Gamma-Ray Astrophysics Laboratory) is dedicated to the fine spectroscopy (2.5 keV FWHM @ 1 MeV) and fine imaging (angular resolution: 12 arcmin FWHM) of celestial gamma-ray sources in the energy range 15 keV to 10 MeV with concurrent source monitoring in the X-ray (3−35 keV) and optical (*V*-band, 550 nm) energy ranges. INTEGRAL was selected in June 1993 as the next medium-size scientific mission within ESA's "Horizon 2000" programme. The mission was conceived as an observatory led by ESA with contributions from Russia (PROTON launcher) and NASA (Deep Space Network ground station). INTEGRAL was originally proposed to ESA in 1989 by an international consortium of high energy astrophysicists led by A. J. Dean (U Southampton) and J. L. Matteson

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(UC San Diego). In this paper we present a high-level overview on all elements of the INTEGRAL Mission.

## 2. Scientific objectives

Gamma-ray astronomy explores the most energetic phenomena that occur in nature and addresses some of the most fundamental problems in physics and astrophysics. It embraces a great variety of gamma-ray continuum and gamma-ray line processes: nuclear excitation, radioactivity, positron annihilation and Compton scattering; and an even greater diversity of astrophysical objects and phenomena: nucleosynthesis, nova and supernova explosions, the interstellar medium, cosmic-ray interactions and sources, neutron stars, black holes, gamma-ray bursts, active galactic nuclei and the cosmic gamma-ray background. Not only do gamma-rays allow us to see deeper into these objects, but the bulk of the power radiated by them is often at gamma-ray energies.

The scientific goals of INTEGRAL will be attained by fine spectroscopy with imaging and accurate positioning of celestial sources of gamma-ray emission. Fine spectroscopy over the entire energy range will permit spectral features to be uniquely identified and line profiles to be measured for physical studies of the source region. The fine imaging capability of INTEGRAL within a large field of view will permit the accurate location and hence identification of the gamma-ray emitting objects with counterparts at other wavelengths, enable extended regions to be distinguished from point sources and provide considerable serendipitous science which is very important for an observatory-class mission.

## 3. Involvement of the scientific community and responsibilities

Following an ESA Announcement of Opportunity (issued 1 July 1994), the Science Programme Committee of ESA approved on 31 May 1995 the scientific payload complement for INTEGRAL, and the INTEGRAL Science Data Centre (ISDC), led by Principal Investigators (PI's). In addition, five Mission Scientists were nominated. The PI's and Mission Scientists together with representatives of the participating agencies constitute the INTEGRAL Science Working Team (ISWT).

All PI teams, providing the payload and data centre, consist of large international collaborations from scientific institutes from almost all 14 ESA member states, USA, Russia, Czech Republic and Poland.

The main tasks of the ISWT are to: (i) maximize the scientific return of INTEGRAL within the technical and programmatic boundary conditions; (ii) ensure that INTEGRAL maintains its principal characteristics as an observatory satisfying the objectives of the scientific community at large; (iii) act as a focus for the interest of the scientific community in INTEGRAL; (iv) maintain contact with the wider astronomical community on matters specific to INTEGRAL so that the community can advise ESA on INTEGRAL's scientific goals from a general point of view.

The key areas of responsibility are distributed as follows: ESA is in charge of the overall spacecraft and mission design, procurement of the spacecraft, participation in payload procurement, instrument integration into the spacecraft, system integration and testing, spacecraft operations, acquisition of data and data distribution to ISDC, and development and operations of the INTEGRAL Science Operations Centre ISOC at ESTEC, Noordwijk. The ESA member states are responsible for the development and procurement of the scientific payload and the INTEGRAL Science Data Centre. Rosaviakosmos and Russain Academy of Sciences provided the PROTON launcher and launch facilities, free of charge in return for scientific observing time, and NASA provided one DSN tracking station, and participated in the payload and the ISDC.

During the development phase of INTEGRAL, the scientific community at large provided very significant input into the design and development of the payload and data centre, and also into the design of the observing programme and science operations. A fruitful mechanism to achieve this feedback was a series of INTEGRAL workshops in 1993 (Durouchoux & Courvoisier 1994), 1996 (Winkler et al. 1997), 1998 (Bazzano et al. 1999), and 2000 (Giménez et al. 2001).

Finally, during the scientific operational phase, the scientific community will participate significantly in the open time programme – a major fraction of the observing programme.

## 4. Mission overview

Traditionally, ESA's scientific directorate approves a budget covering all project development phases starting from Phase B including launch and two years of nominal mission science operations. In order to stay within the ESA budget ceiling which was available for INTEGRAL as a medium-sized mission within "Horizon 2000" at time of approval in 1993, it was obvious – already during phase A study in the early 90's – that one had to embark on novel routes to successfully meet the budget constraints. The following major elements were successfully implemented during the development phase of the INTEGRAL project: (i) common design and parallel development, with XMM-Newton, of the spacecraft's service module; (ii) the use of a non-ESA launcher, a PROTON launch vehicle provided by Rosaviakosmos and Russian Academy of Sciences in exchange for scientific data; (iii) contribution of ground station support by NASA, and (iv) the development, procurement and operation of the science data centre (ISDC).

The spacecraft (Jensen et al. 2003) consists of a service module (bus) containing all spacecraft subsystems and a payload module containing the scientific instruments. The service module has been developed in parallel for two ESA scientific missions, INTEGRAL and XMM-Newton. The simplicity of the interface between service and payload module was a major design driver. A modular approach has been conceived to allow for a parallel development, assembly, integration and test of service and payload module, respectively. The spacecraft has been built under ESA contract by a large industrial consortium, led by Alenia Spazio as prime contractor.

INTEGRAL, with a total launch mass of about 4 t (Fig. 1), was launched by a four-stage PROTON from

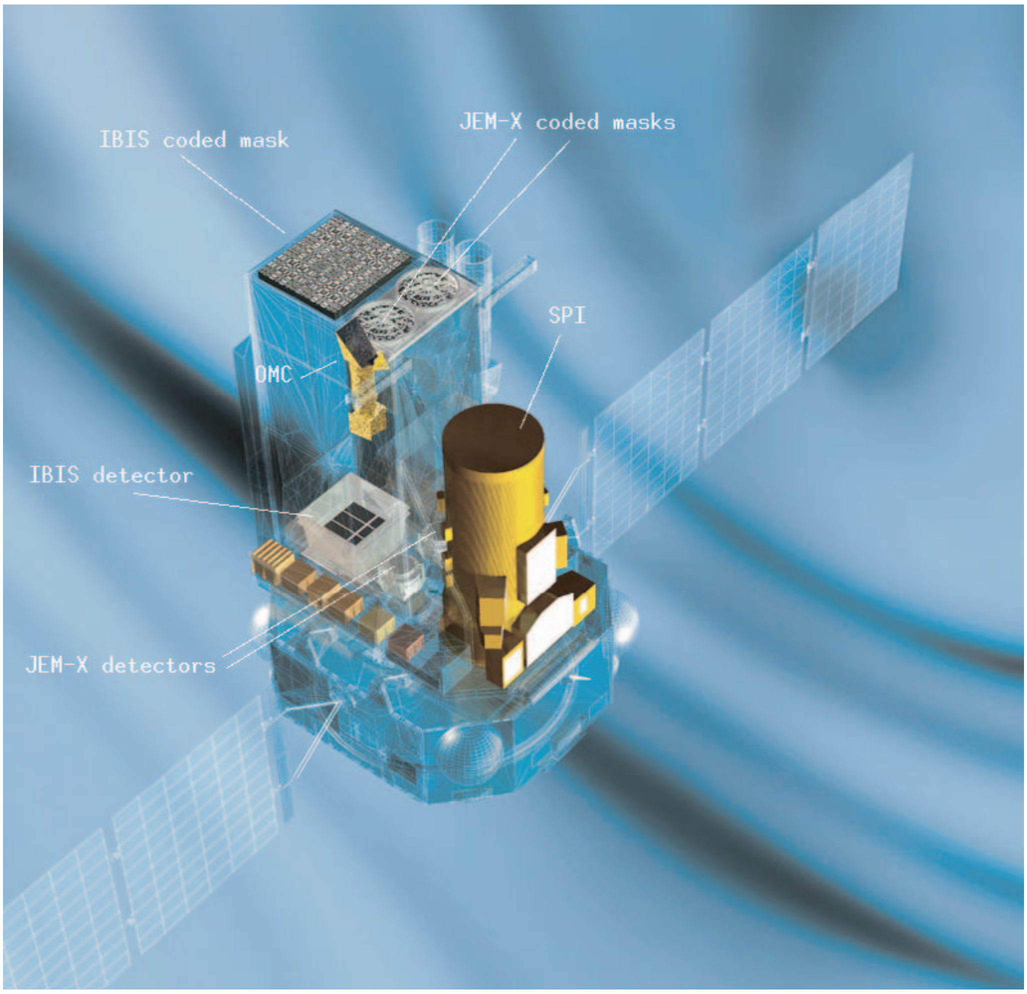


**Fig. 1.** The INTEGRAL spacecraft. Dimensions are (5 × 2.8 × 3.2) m. The deployed solar panels are 16 metres across. The mass is 4 t (at launch), including 2 t of payload.

Baikonur/Kazakhstan on 17 October 2002. It was inserted into a geosynchronous highly eccentric orbit with high perigee in order to provide long periods of uninterrupted observation with nearly constant background and away from trapped radiation (electron and proton radiation belts). The initial orbital parameters are: 72-hour orbit with an inclination of 52.2 degrees, a height of perigee of 9000 km and a height of apogee of 154 000 km. Owing to background radiation effects in the high-energy detectors, scientific observations are carried out while the satellite is above a nominal altitude of 60 000 km (approaching radiation belts) and above 40 000 km (leaving radiation belts). This means that ~90% of the time spent in the orbit provided by the PROTON can be used for scientific observations (real-time, 108 kbps science telemetry). An on-board particle radiation monitor allows an assessment of the radiation environment local to the spacecraft.

## 5. Payload

INTEGRAL carries two main gamma-ray instruments, the spectrometer SPI (Vedrenne et al. 2003) – optimized for the high-resolution gamma-ray line spectroscopy (20 keV–8 MeV), and the imager IBIS (Ubertini et al. 2003) – optimized for high-angular resolution imaging (15 keV–10 MeV). Two monitors, JEM-X (Lund et al. 2003) in the (3−35) keV X-ray band, and OMC (Mas-Hesse et al. 2003) in optical Johnson *V*-band complement the payload.

The spectrometer, imager and X-ray monitor share a common principle of operation: they are all coded aperture mask telescopes. The coded mask technique is the key for imaging, which is all-important in separating and locating sources. It also provides near perfect background subtraction because for any particular source direction the detector pixels can be considered to be split into two intermingled subsets, those capable of viewing the source and those for which the flux is blocked by opaque mask elements. Effectively the latter subset provide an exactly contemporaneous background measurement for the former, made under identical conditions.

The payload was extensively calibrated pre-launch on instrument and system level. During the early mission phase, the in-flight calibration was initially performed on Cyg X−1, and empty fields, and completed later – in February 2003 due to visibility constraints – using the Crab nebula and pulsar.

All instruments (Fig. 1 and Table 1) are co-aligned with overlapping fully coded field–of–views ranging from 4.8° diameter (JEM-X), 5° × 5° (OMC), to 9° × 9° (IBIS) and

**Table 1.** INTEGRAL payload: key parameters.

| Parameter | SPI | IBIS |
|---|---|---|
| Energy range | 18 keV–8 MeV | 15 keV–10 MeV |
| Detector | 19 Ge detectors, each $(6 \times 7)$ cm cooled @ 85 K | 16384 CdTe dets, each $(4 \times 4 \times 2)$ mm 4096 CsI dets, each $(8.4 \times 8.4 \times 30)$ mm |
| Detector area ($cm^2$) | 500 | 2600 (CdTe), 2890 (CsI) |
| Spectral resolution (FWHM) | 3 keV @ 1.7 MeV | 8 keV @ 100 keV |
| Continuum sensitivity (photons $cm^{-2}$ $s^{-1}$ $keV^{-1}$) ($\Delta E = E/2$, $3\sigma$, $10^6$ s) | $5.5 \times 10^{-6}$ @ 100 keV $1.2 \times 10^{-6}$ @ 1 MeV | $6 \times 10^{-7}$ @ 100 keV $5 \times 10^{-7}$ @ 1 MeV |
| Line sensitivity (photons $cm^{-2}$ $s^{-1}$) ($3\sigma$, $10^6$ s) | $3.3 \times 10^{-5}$ @ 100 keV $2.4 \times 10^{-5}$ @ 1 MeV | $1.9 \times 10^{-5}$ @ 100 keV $3.8 \times 10^{-4}$ @ 1 MeV |
| Field of view (fully coded) | 16° (corner to corner) | $9° \times 9°$ |
| Angular resolution (FWHM) | 2.5° (point source) | 12′ |
| Source location (radius) | ≤1.3° (depending on source strength) | ≤1′ (for $10\sigma$ source) |
| Absolute timing accuracy ($3\sigma$) | ≤200 $\mu$s | ≤200 $\mu$s |
| Mass (kg) | 1309 | 746 |
| Power [max/average] (W) | 385/110 | 240/208 |
| **Parameter** | **JEM−X** | **OMC** |
| Energy range | 4 keV–35 keV | 500 nm–600 nm |
| Detector | Microstrip $Xe/CH_4$−gas detector (1.5 bar) | CCD + $V$-filter |
| Detector area ($cm^2$) | 500 for each of the two JEM-X detectors[a] | CCD: $(2061 \times 1056)$ pixels Imaging area $(1024 \times 1024)$ pixels |
| Spectral resolution (FWHM) | 2.0 keV @ 22 keV | – |
| Continuum sensitivity[b] (photons $cm^{-2}$ $s^{-1}$ $keV^{-1}$) ($3\sigma$, $10^6$ s) | $1.2 \times 10^{-5}$ @ 6 keV $1.3 \times 10^{-5}$ @ 30 keV | – – |
| Line sensitivity[b] (photons $cm^{-2}$ $s^{-1}$) ($3\sigma$, $10^6$ s) | $1.9 \times 10^{-5}$ @ 6 keV $8.5 \times 10^{-5}$ @ 30 keV | – – |
| Limiting magnitude (mag) ($3\sigma$, 5000 s) | – | 17.8 |
| Field of view (fully coded) | 4.8° | $5° \times 5°$ |
| Angular resolution (FWHM) | 3′ | 25″ |
| $10\sigma$ source location (radius) | ≤30″ | 6″ |
| Absolute Timing accuracy ($3\sigma$) | ≤200 $\mu$s | ≥1 s |
| Mass (kg) | 65 | 17 |
| Power [max/average] (W) | 50/37 | 20/17 |

[a] At the moment, only one of the two JEM-X detectors is being operated.
[b] Assumes operation of both detectors.

16° corner-to-corner (SPI), and they are operated simultaneously, so, an observer receives all data from all 4 instruments. For comparison, Table 2 summarizes key performance parameters of INTEGRAL and some previous gamma-ray experiments.

## 6. Ground segment

The ground segment consists of two major elements, the Operations Ground Segment (OGS) and the Science Ground Segment (SGS). The OGS, consisting of the ESA and NASA ground stations and the Mission Operations Centre at ESOC, implements the observation plan within the spacecraft system constraints into an operational command sequence. In addition, the OGS performs all standard spacecraft and payload operations and maintenance tasks. The SGS itself consists of two components, the INTEGRAL Science Operations Centre (ISOC, Much et al. 2003) and the INTEGRAL Science Data Centre (ISDC, Courvoisier et al. 2003). The ISOC processes the accepted observation proposals into an optimised observation plan which consists of a time line of target pointings plus the corresponding instrument configuration. ISOC is also responsible for the implementation of Target of Opportunity observations within the pre-planned observing programme. The ISDC receives the science telemetry plus the relevant ancillary spacecraft data from the OGS. Final data products will be distributed to the observer and archived for later use by the science community.

## 7. Observing programme

INTEGRAL was conceived from its initial study phase in 1989 as an observatory-type mission (nominal lifetime 2 years,

**Table 2.** INTEGRAL and some previous gamma-ray experiments.

| Parameter | OSSE | COMPTEL | EGRET | BATSE | SIGMA[c] | HEAO–3 | INTEGRAL |
|---|---|---|---|---|---|---|---|
| Energy range (MeV) | 0.05–10 | 0.7–30 | 20–30 000 | 0.03–1.9 | 0.035–1.3 | 0.05–10 | 0.004–10 (JEM-X, SPI, IBIS) |
| Energy resolution (%) | 5–12 | 4–15 | ~20 | 20–32 | 8–16 | 0.2 @ 1.8 MeV | 0.16 @ 1.8 MeV (SPI) |
| Source position localization | 10′ | 0.5° – 1° | ≤10′ | 1° | ~1′ | none | ≤1′–1.5′ (IBIS) |
| Field of View | $3.8° \times 11.4°$ | 1 sr | 0.6 sr | Earth occultation | $4.7° \times 4.3°$ fully coded | $30° \times 30°$ | 16° fully coded (SPI) |
| Narrow line sens. (ph cm$^{-2}$ s$^{-1}$) ($3\sigma$, $10^6$ s) | $7 \times 10^{-5}$ @ 1 MeV | $5 \times 10^{-5}$ @ 1 MeV | n/a | – | $\sim 8 \times 10^{-4}$[b] @ 511 keV | $\sim 2 \times 10^{-4}$[e] | $2.4 \times 10^{-5}$ @ 1 MeV (SPI) |
| Continuum sens. (ph cm$^{-2}$ s$^{-1}$ keV$^{-1}$) ($3\sigma$, $10^6$ s) | $2 \times 10^{-7}$ @ 1 MeV $5 \times 10^{-7}$ @ 100 keV | $1.7 \times 10^{-7}$ @ 1 MeV | $5 \times 10^{-8}$ ≥100 MeV | $\sim 2 \times 10^{-3}$[a] 25–35 keV | $7 \times 10^{-6}$ @ 100 keV | $\sim 1 \times 10^{-5}$ entire survey @ 100 keV[d] | $5 \times 10^{-7}$ @ 1 MeV (IBIS) |
| Years of operation | 1991–2000 | 1991–2000 | 1991–2000 | 1991–2000 | 1989–1998 | 1979–1981 | 2002 → |

[a] Calculated from Shaw S. E., et al. 2001, in Exploring the Gamma-ray Universe, Proc. of the 4th INTEGRAL Workshop, ed. A. Giménez et al., ESA SP-459, 521.
[b] Goldwurm A., et al. 1992, ApJ, 369, 79.
[c] Paul J., et al. 1991, Adv. Space Res., 11 (8), 289.
[d] Ulmer M. P., et al. 1991, ApJ, 369, 485.
[e] Line sensitivity from `http://heasarc.gsfc.nasa.gov/docs/heao3/heao3_about.html`.

extensions up to 5 years possible). Most of the total observing time (65% during year 1, 70% year 2, 75% year 2+) is awarded as the General Programme to the scientific community at large. Typical observations last from 100 ksec up to about two weeks. Proposals for observations are selected on their scientific merit only by a single Time Allocation Committee (TAC). These selected observations are the base of the general programme. The first call (AO-1) for observation proposals was issued on 1 Nov. 2000 with a proposal submission deadline by 16 February 2001. This first call was extremely successful as it resulted in an oversubscription of the proposed observing time by a factor of 19. The final AO-1 programme (Figs. 2, 3) as selected by the TAC still carries an oversubscription of a factor ~2. The call for AO-2 will be released in summer 2003. The final AO-2 programme will run for 12 months, starting December 2003.

As a return to those scientific collaborations and individual scientists who contributed to the development, design and procurement of INTEGRAL and who are represented in the INTEGRAL Science Working Team (ISWT), a portion of the total scientific observing time, the guaranteed time, will be used for their Core Programme (Winkler 2001) observations. The guaranteed time amounts during the first year of nominal operations to 35% (or $\sim 9.3 \times 10^6$ s) of the total annual observing time ($\sim 26.6 \times 10^6$s). The Core Programme during AO-1 consists of three elements, a deep exposure (4.3 Ms) of the Galactic central radian, scans of the Galactic plane (2.3 Ms), pointed observations (Vela region, 1 Ms) and TOO follow-up observations (1.7 Ms). First results from the General Programme and Core Programme observations can be found elsewhere in this volume.

## 8. Conclusions and outlook

The flawless launch of INTEGRAL and – as reported elsewhere in this volume – the very successful and smooth start of the INTEGRAL mission, due to the excellent performance of spacecraft, instruments and ground segment, are the culmination of a development period which started more than 14 years ago. Many science results are coming in already now (for scheduling information on executed, planned and future observations, please consult `http://www.rssd.esa.int/integral`) and the prospects for the remaining part of the nominal mission are excellent. INTEGRAL is currently funded until end of nominal mission, i.e. December 2004. Preparations have begun to obtain mission extension approval beyond this point in time.

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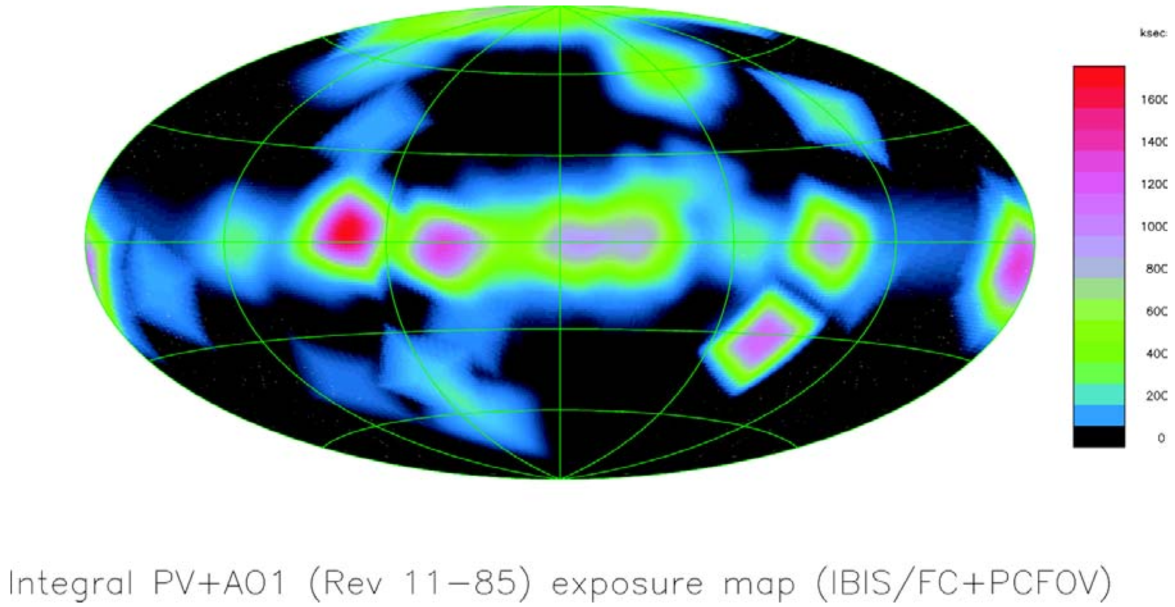


**Fig. 2.** Exposure map of the INTEGRAL/IBIS imager, partially coded FOV in galactic co-ordinates. Scientific observations during performance and verification (PV) phase (Nov.–Dec. 2002) and AO-1 observations (Dec. 2002–June 2003) have been included. Figure produced by E. Kuulkers (ESA/ESTEC-ISOC).

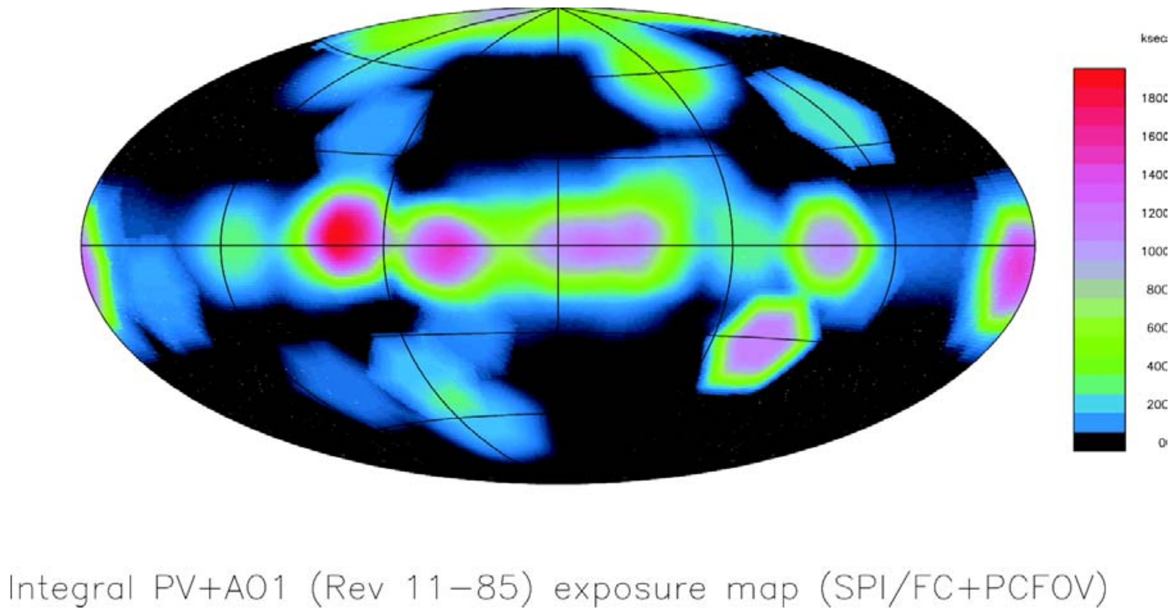


**Fig. 3.** Exposure map of the INTEGRAL/SPI spectrometer, partially coded FOV in galactic co-ordinates. Scientific observations during performance and verification (PV) phase (Nov.–Dec. 2002) and AO-1 observations (Dec. 2002–June 2003) have been included. Figure produced by E. Kuulkers (ESA/ESTEC-ISOC).

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